



# Artificial Software Diversification for WebAssembly

JAVIER CABRERA-ARTEAGA

Doctoral Thesis  
Supervised by  
Benoit Baudry and Martin Monperrus  
Stockholm, Sweden, 2023

TRITA-EECS-AVL-2020:4  
ISBN 100-

KTH Royal Institute of Technology  
School of Electrical Engineering and Computer Science  
Division of Software and Computer Systems  
SE-10044 Stockholm  
Sweden

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges  
till offentlig granskning för avläggande av Teknologie doktorexamen i elektroteknik  
i .

© Javier Cabrera-Arteaga , date

Tryck: Universitetsservice US AB

**Abstract**

[1]

**Keywords:** Lorem, Ipsum, Dolor, Sit, Amet

**Sammanfattning**

[1]

# O

## LIST OF PAPERS

### 1. *WebAssembly Diversification for Malware Evasion*

Javier Cabrera-Arteaga, Tim Toady, Martin Monperrus, Benoit Baudry  
*Computers & Security, Volume 131, 2023*

<https://www.sciencedirect.com/science/article/pii/S016740482302067>

### 2. *Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly*

Javier Cabrera-Arteaga, Nicholas Fitzgerald, Martin Monperrus, Benoit Baudry

### 3. *Multi-Variant Execution at the Edge*

Javier Cabrera-Arteaga, Pierre Laperdrix, Martin Monperrus, Benoit Baudry

*Conference on Computer and Communications Security (CCS 2022), Moving Target Defense (MTD)*

<https://dl.acm.org/doi/abs/10.1145/3560828.3564007>

### 4. *CROW: Code Diversification for WebAssembly*

Javier Cabrera-Arteaga, Orestis Floros, Oscar Vera-Pérez, Benoit Baudry, Martin Monperrus

*Network and Distributed System Security Symposium (NDSS 2021), MADWeb*

<https://doi.org/10.14722/madweb.2021.23004>

### 5. *Superoptimization of WebAssembly Bytecode*

Javier Cabrera-Arteaga, Shrinish Donde, Jian Gu, Orestis Floros, Lucas Satabin, Benoit Baudry, Martin Monperrus

*Conference Companion of the 4th International Conference on Art, Science, and Engineering of Programming (Programming 2021), MoreVMs*

<https://doi.org/10.1145/3397537.3397567>

### 6. *Scalable Comparison of JavaScript V8 Bytecode Traces*

Javier Cabrera-Arteaga, Martin Monperrus, Benoit Baudry  
*11th ACM SIGPLAN International Workshop on Virtual Machines and*

*Intermediate Languages (SPLASH 2019)*  
<https://doi.org/10.1145/3358504.3361228>

# 0

## ACKNOWLEDGEMENT



# O

## ACRONYMS

List of commonly used acronyms:

**Wasm** WebAssembly



# Contents

<b>List of Papers</b>	<b>iii</b>
<b>Acknowledgement</b>	<b>v</b>
<b>Acronyms</b>	<b>vii</b>
<b>Contents</b>	<b>1</b>
<b>I Thesis</b>	<b>3</b>
<b>1 Introduction</b>	<b>5</b>
1.1 Background . . . . .	5
1.2 Problem statement . . . . .	5
1.3 Automatic Software diversification requirements . . . . .	5
1.4 List of contributions . . . . .	5
1.5 Summary of research papers . . . . .	6
1.6 Thesis outline . . . . .	6
<b>2 Background and state of the art</b>	<b>7</b>
2.1 WebAssembly . . . . .	7
2.1.2 Generating WebAssembly programs . . . . .	7
2.1.3 WebAssembly's binary format . . . . .	9
2.1.4 WebAssembly's runtime structure . . . . .	11
2.1.5 WebAssembly's control flow . . . . .	13
2.1.6 WebAssembly's ecosystem . . . . .	14
2.1.7 WebAssembly binary analysis . . . . .	16
2.1.8 WebAssembly opportunities . . . . .	17
2.2 Software diversification . . . . .	18
2.2.2 Generating Software Diversification . . . . .	18
2.2.3 Variants generation . . . . .	18

2.2.4	Variants equivalence . . . . .	18
2.2.5	Defensive Diversification . . . . .	18
2.2.6	Offensive Diversification . . . . .	18
<b>3</b>	<b>Automatic Software Diversification for WebAssembly</b>	<b>19</b>
3.1	CROW: Code Randomization of WebAssembly . . . . .	20
3.1.2	Enumerative synthesis . . . . .	21
3.1.3	Constant inferring . . . . .	22
3.1.4	CROW instantiation . . . . .	23
3.2	MEWE: Multi-variant Execution for WebAssembly . . . . .	25
3.2.2	Multivariant generation . . . . .	27
3.3	WASM-MUTATE: Fast and Effective Binary for WebAssembly . . . . .	29
3.3.2	WebAssembly Rewriting Rules . . . . .	29
3.3.3	E-Graphs traversals . . . . .	31
3.3.4	WASM-MUTATE instantiation . . . . .	32
3.4	Comparing CROW, MEWE, and WASM-MUTATE . . . . .	34
3.4.2	Security applications . . . . .	37
3.5	Conclusions . . . . .	38
<b>4</b>	<b>Exploiting Software Diversification for WebAssembly</b>	<b>39</b>
4.1	Offensive Diversification: Malware evasion . . . . .	39
4.1.2	Objective . . . . .	39
4.1.3	Approach . . . . .	39
4.1.4	Results . . . . .	39
4.2	Defensive Diversification: Speculative Side-channel protection . . . . .	39
4.2.2	Threat model . . . . .	40
4.2.3	Approach . . . . .	40
4.2.4	Results . . . . .	40
<b>5</b>	<b>Conclusions and Future Work</b>	<b>41</b>
5.1	Summary of technical contributions . . . . .	41
5.2	Summary of empirical findings . . . . .	41
5.3	Summary of empirical findings . . . . .	41
5.4	Future Work . . . . .	41
<b>II</b>	<b>Included papers</b>	<b>43</b>
	Superoptimization of WebAssembly Bytecode	47
	CROW: Code Diversification for WebAssembly	49

<i>CONTENTS</i>	3
Multi-Variant Execution at the Edge	<b>51</b>
WebAssembly Diversification for Malware Evasion	<b>53</b>
Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly	<b>55</b>
Scalable Comparison of JavaScript V8 Bytecode Traces	<b>57</b>



## **Part I**

# **Thesis**

